Economic Evaluation of Turbining Potential in Drinking Water Supply Networks

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Introduction

The strategy document « Vision Energétique de la Suisse en 2050 », established by the Center for Energy Policy and Economics of Swiss Federal Institute of Technology (ETHZ), reveals the first impacts of climate change and underlines the fact, that the increasing energy consumption will influence the climate irreversibly in next few years and generate tremendous social, ecological and economic impacts. The only way to guarantee simultaneously the security of local energy supply as well as to protect the environment is the development and use of sustainable power supply systems.

From this point of view, a sustainable energy production by small and micro hydropower plants becomes important. By its energetic potential, its low construction costs and its common availability in mountainous regions, drinking water turbining is especially attractive. For promoting this source of renewable energy, a computer tool was developed, evaluating the economic potential of existing supply networks.

The TURBEAU software, developed at *Ecole Polytechnique Fédérale de Lausanne* (EPFL) in the framework of a project supported by the hydropower and energy department of Valais canton in Switzerland, is based on a simple and quick approach, allowing the definition of the economic turbining potential in drinking water networks with a minimum of input data. The numerical tool evaluates different locations for the turbine and its supply. The result should motivate the construction of economically interesting small hydropower plants, and therefore increase the production of renewable energy.

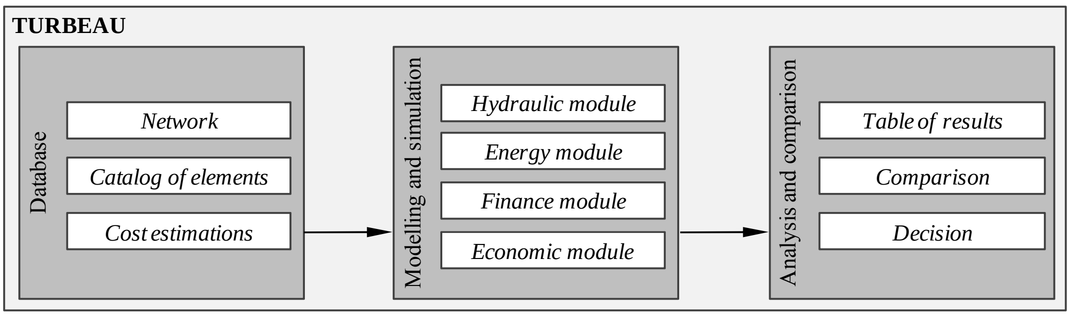

Fig. 1. Flow chart of TURBEAU.

A wide range of elements provides the system modelling by the user, taking into account the topological and geometrical characteristics of the network as well as the supply and consumption conditions. Cost indications are available for a preliminary economic analysis. The total evaluation cycle includes five steps: Calculation of the hydraulic profile of the network, definition of the energetic potential, financial analysis of configuration alternatives, economic life cycle analysis and comparison of optimised solutions (Fig. 1).

1. Methodology

TURBEAU is a simple numerical tool allowing a quick evaluation of the economic hydropower potential in an existing water supply network. It introduces an energetic objective by conserving the priority of water supply. Based on a balancing algorithm for the resolution of pressure networks, the software allows reproducing the network elements by an interactive graphical interface and simulating its hydraulic behaviour.

Four modules have to be passed trough during a simulation: The first one concerns hydraulic calculations of head losses in the whole modelled system. The second module computes the power and energy potential. The third one evaluates the construction and installation costs of the power plant as well as associated costs. The last step concerns the economic life cycle analysis, including the calculation of the cost price of the generated energy as well as an overall balance of the project. After passing the four modules, the user is able to compare the alternatives, to define the optimal place for the installation of the hydropower plant and to decide about its economical feasibility. TURBEAU is not a tool for demand managing in the network. It does not evaluate eventual lack or abundance either.

1.1 Hydraulic module

The objective of the hydraulic module is the definition of flow distribution and energy grade line in the whole water supply network. For modelling the system, six basic elements are defined by the following specific functions:

- **Reservoir**. Drinking water reservoirs are just used as head ponds and not as storage basins. They guarantee the required pressure in the shafts.
- **Source**. Sources correspond to the input generator of the model. Every source introduces a hydrograph of the available monthly discharges.
- **Consumption**. The demand is defined as a hydrograph of the required monthly discharges. This element is essential for the hydraulic calculation of the network. If the consumption is higher or lower than the available volumes, the lack of flow or the overflow are indicated at the upstream reservoir.
- **Junction**. Junctions are used for dividing flow from one to several pipes. They also allow deriving water to other systems or reservoirs.
- **Flow regulator**. The discharge of a pipe can be regulated by adding an additional local head-loss. In common drinking water supply systems, these elements avoid overpressure. The lost energy could also be used for producing hydropower. The implantation of a turbine allows regulating the flow as well.
- **Turbine**. In a drinking water supply system, discharges are generally low, but the hydraulic heads often important, between 60 and 600 m. Consequently Pelton turbines are the most adapted hydraulic machines (Chapallaz et al. 1995). The by-pass allows evacuating flow when the turbine is out of order or needed flow is higher than the maximal discharge of the turbine. This explains why the by-pass is integrated in the element turbine.

These elements are linked by pipes:

- **Pipe**. The pressure head in the pipes is assured by reservoirs. Friction losses in pipes are computed by applying the Colebrook-White formula (Keady 1995). Only linear head-losses are taken into account, local ones are neglected.

The hydraulic module defines the capacity of the pipes and the energy grade line under steady flow conditions. By taking into account the flow and the maximal capacity of each pipe at any point, the system is equilibrated. The iterative resolution method is based on two physical principles applied for every pipe, delimited by two nodes. The friction head losses are first calculated. Then the head is defined at every node considering conservation of energy between starting and ending point of each pipe. The discharge is determined by applying the flow conservation criteria at any node. By knowing the geometrical (length and diameter) and material characteristics (roughness coefficient), discharge as well as hydraulic head can be calculated at every node of the whole network. The iterative calculation stops when the obtained deviation between two steps is smaller than a predefined limit.

1.2 Energy module

The energy module defines the quantity of producible energy by every potential alternative for comparing them. The discharges are given as monthly average values. For defining the design discharge, the net power has to be computed as a function of discharge and head. The efficiency coefficient of the turbo-alternator group depends on the ratio between design and effective flow. Design flow is defined as the discharge with the highest efficiency of the turbo-alternator. For discharge ratio between 5% and 100%, efficiency increases from 57% to 85%. For higher flows up to 140%, it decreases to 82%. By knowing the net power, the producible energy can be defined by considering the operating time.

1.3 Finance module

Beyond physical and topological characteristics of the system, financial criteria, such as the total investment costs as well as the maintenance costs, have to be taken into account for a global evaluation of the hydropower project. The costs of the different constitutive elements can be entered manually when knowing them. Because of the usual lack of this knowledge, the costs have been evaluated by analysis of real projects in 2008 as follows:

- **Pipes**. The cost of new pipes C_P [CHF] takes into account the pipe furniture itself, valve and secondary elements as well as transport, excavation and installation. TURBEAU only needs the indication of pipe diameter D [mm] and length L_P [m] for defining this cost ($C_P = 0.00148\ D^2 + 0.5588\ D + 184.322$). This simplified evaluation offers a big advantage for a first draft design, but is also source of uncertainty. All costs not linked to drinking water supply (bigger diameter or stronger pipe) are affected to the hydropower project. If more than one turbine project are considered in a network, the over costs of the pipes are equally divided among them.
- **Turbo-alternator group**. Turbine, alternator, control board, alarm system as well as installation and test procedure are taken into account in the group. This cost C_{TA} [CHF] is only depending on installed power P [kW] ($C_{TA} = -2.487\ P^2 + 2189.6\ P + 5603.7$). For plants with less than 20 kW installed power, a minimal cost of CHF 48'000 is estimated.
- **Connection to electricity network**. The connection to the electricity network C_{EN} [CHF] is compound of a basic amount as well as a part for wiring, which depends on the distance between powerhouse and current line L_{EN} [m] ($C_{EN} = 20'000 + 70\ L_{EN}$, if voltage ≤ 400 V, $C = 30'000 + 90\ L_{EN}$, if voltage > 400 V).
- **Switchgear**. The switchgear between the electricity network and the plant generates a cost C_{SG} [CHF] depending linearly on the installed power P [kW] ($C_{SG} = 180\ P$).
- **Transformer**. Like the switchgear, the cost of the transformer C_T [CHF] increases linearly by increasing power P [kW] ($C_T = 3'500 + 120\ P$).
- **Remote control system**. Remote control systems are not absolutely essential but nowadays usual. That is why TURBEAU foresees a fix amount of CHF 20'000 for this electronic component.
- **By-pass**. The by-pass is an essential element for a reliable management of the plant. A unit cost of CHF 20'000 is taken into account.
- **Powerhouse**. The powerhouse contains the main hydraulic, mechanic and electronic elements of the plant. Its cost C_{PH} [CHF] is a function of the installed power P [kW] ($C_{PH} = 1'200\ P$).
- **Access**. A road affords the access to the powerhouse during the construction period and for exploitation needs. TURBEAU takes into account its length L_R [m] for defining the cost C_R [CHF] ($C_R = 100\ L_R$).
- **Construction site**. The cost for the construction site C_{CS} [CHF] – access, equipment and security – depends on the dimensions of the project. The installed power P [kW] is a useful indicator for this ($C_{CS} = 120\ P$).
- **Diverse**. Costs for project design and planning, site management, building licence, unexpected things etc. can be manually entered in the field Diverse.

For most of the elements, an good approximation of prices is possible by analysing a range of data and by using unit prices. However, certain elements are especially difficult to number due to a lack of information. To deal with the uncertainty of date incompleteness, TURBEAU proposes economical scenarios – a pessimistic and an optimistic one. For three particular elements, an upper and lower value is taken into account: The length of the connection line to the next electricity network varies between 100 m and 1'000 m., the length of the road is either 50 m or 200 m and the costs for the powerhouse can be neglected when an existing building is available.

1.4 Economic module

The economic module evaluates the profitability of every alternative. This is based on several economic indicators:

- **Capital cost**. From the sum of the raw costs, eventual subsidies have first to be deducted. By adding inflation and interest charges for the construction period, the capital cost is then calculated.
- **Annual costs**. By taking into account a constant annuity and 10% of the raw costs for administration, taxes and assurances, the annual cost of the project is defined.
- **Maintenance costs**. The maintenance costs are evaluated by two different approaches. An empirical formula uses annual electricity output for the estimation. The other method defines for every element the maintenance costs independently by applying individual percentages of their raw costs.
- **Annual input**. The annual input is the product of the annual electricity production by the price of energy. The user can define this price individually or the guide-lines of the aid programme of the Swiss Confederation can be applied.
- **Annual gain**. The annual gain corresponds to the difference between the annual input and the total costs.
- **Cost price**. The cost price is calculated by dividing the annual costs by the annual energy production. It is an important parameter to test the cost effectiveness of a project by comparison to the market prices.

In the economic module several basic parameters have to be defined. The Swiss government supports small hydropower by attractive electricity tariffs as defined in the *Loi sur l'Approvisionnement en Electricité* (LApEl) and the *Ordonnance sur l'énergie* (OEne). For the definition of the preferential unit price, several characteristics of the plant are taken into account. The law also indicates a construction period of 6 months, a damping time of 25 years, an interest rate of 4% as well as an inflation rate of 1%. These values are set in TURBEAU, but can be changed easily by the user.

2. Software

The modules presented in chapter 1 allow the user modelling the whole or a part of a drinking water supply system. TURBEAU software is written in VB.net according to an object orientated approach. The interface contains two main toolbars. The first one, located in the upper horizontal band of the window, contains the basic functions. The second one, on the left vertical margin, includes the elements for network modelling (Fig. 2).

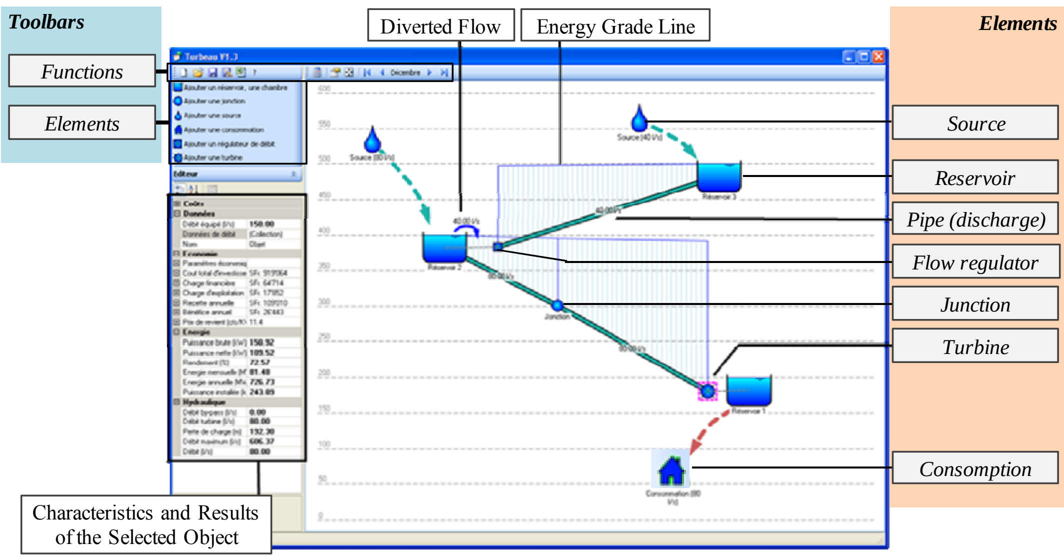

Fig. 2. Layout of the user interface of TURBEAU with toolbars and the different modelling elements.

2.1 Basic functions

The basic functions help the user to handle the simulations. Some of them are commonly known, as for example opening or saving the project. Others are more specific to TURBEAU as the time selection. Table 1 gives an overview on all the basic functions:

Tab 1.Basic functions in TURBEAU.

Icon	Basic Function	Explanation
	New Project	Creation of new project without saving the existing one
	Open Project	Opening of an existing file
	Save Project	Saving of a new project or of the modifications (*.tbo)
	Save Project as	Saving of the project with a new name (*.tbo)
	Export to EXCEL	Export of parameters and results to Microsoft.Excel (*.xls)
	Characteristics	Basic information about the software TURBEAU
	Start calculation	Start of iteration process
	Parameters	Physical parameters : gravity (9.81 m/s) temperature of water (5°C) Numerical parameters : precision (10^{-6} l/s) relaxation coefficient (0.25)
	Window	Showing the entire network in the window of the interface
Décembre	*Time selection*	Choice of the month for showing results in the interface

2.2 Elements

The list of elements is located on the left part of the window. Elements can be introduced in the working space and erased at any moment of the modelling process. Reservoirs, junctions, flow regulators and turbines are linked by pipes. By mouse-clicking on the elements, the user gets information about the hydraulic and economic parameters and he is able to adapt them in the menu appearing on the left part under the list of elements (Tab. 2).

Tab 2. Elements for modelling in TURBEAU.

Icon	Elements	Input data
	Reservoir	Name and level [m a.s.l.]
	Junction	Name
	Source	Name and hydrograph of monthly inflow [l/s]
	Consumption	Name and hydrograph of monthly outflow [l/s]
	Flow regulator	Name and hydrograph of monthly flow [l/s]
	Turbine	Name, design flow [l/s], hydrograph of monthly turbined discharge [l/s], costs [CHF], economic parameters (interest rate etc.)
	Pipe	Name, diameter [mm], length [m], roughness [mm], costs [CHF]

Turbines and pipes are the only elements containing economic parameters. In an existing water supply network, pipes do not have to be changed. That is why the default costs for them are put to zero. Without intervention by the user, the default cost estimation formulas for the equipment of the power plant are used as well. The shown values are the pessimistic ones. The selling price of electricity is initially set to 15 cts/kWh. The resulting cost price is then compared to the price obtained when applying the remuneration directive issued from the Swiss legislation: *Loi sur l'Approvisionnement en Electricité* (LApEl) and *Ordonnance sur l'énergie* (OEne). The user is free to modify the initial price after the first simulation.

2.3 Modelling and simulation

TURBEAU requires a Windows XP or more recent Microsoft system software. The computer does not need especially high processing power. The operation language is French. The modelling of a new project contains three steps: creation of the project, selection of elements and connection between them.

1. A new project has to be created or an existing can be opened
2. By clicking on the elements in the toolbar, new elements appear in the centre of the interface. The placement of them can be changed by "drag and drop". Reservoirs are located at the right selected level.
3. By clicking on the elements of the network, their properties can be visualized and adapted.
4. A double-click on an element introduces the linking process, which stops by a click on another element or by an arbitrary key press. The pipe appears immediately and its properties have to be defined.
5. When the implantation process is finished, the simulation starts by clicking on the corresponding icon.

After the hydraulic equilibrium process, results are shown in the properties list of the elements. By clicking on a turbine, results from the hydraulic, energy, finance and economic modules appear. These can be easily exported to Microsoft.Excel. The synthesis report is structured in five tables. The first one (Fig. 3) contains the main economic parameters and results of the plants for the optimistic and pessimistic scenario. The following tables contain monthly turbined flows, levels of the reservoirs, pipe characteristics and a detailed definition of the two economic scenarios.

Interest rate [%]		Inflation rate [%]			Construction time [years]		Damping time [years]		Annuity [%]	
4		1			0.5		25		6.4	
	Hydraulic module		Energy module		Economic module					
Sites	Design flow	Head	Power	Energy	Total investment	Capital costs	Maintenance costs	Annual output	Annual earnings	Cost price
	[l/s]	[m]	[kW]	[MWh/year]	[CHF]	[CHF/year]	[CHF/year]	[CHF/year]	[CHF/year]	[cts/kWh]
Plant OPT	80	391.13	308.13	1242.15	2134300	150300	21200	186300	14900	13.8
Plant PES	80	391.13	308.13	1242.15	2602300	183200	23300	186300	-20300	16.6
Plant OPT	80	767	601.19	2260.73	2241000	157800	20800	339100	160500	7.9
Plant PES	80	767	601.19	2260.73	3076500	216600	24800	339100	97700	10.7

Fig. 3. Table of results 1 of TURBEAU exported in EXCEL for a network with two turbines.

3. Examples

Two examples are presented, one is a simple serial network with only one source (Fig. 4 on the left) and the other a more complicated parallel one with several sources and consumptions (Fig. 4 on the right). Both correspond to real cases and the costs can be compared to actual market conditions. Only the names of the places have been changed.

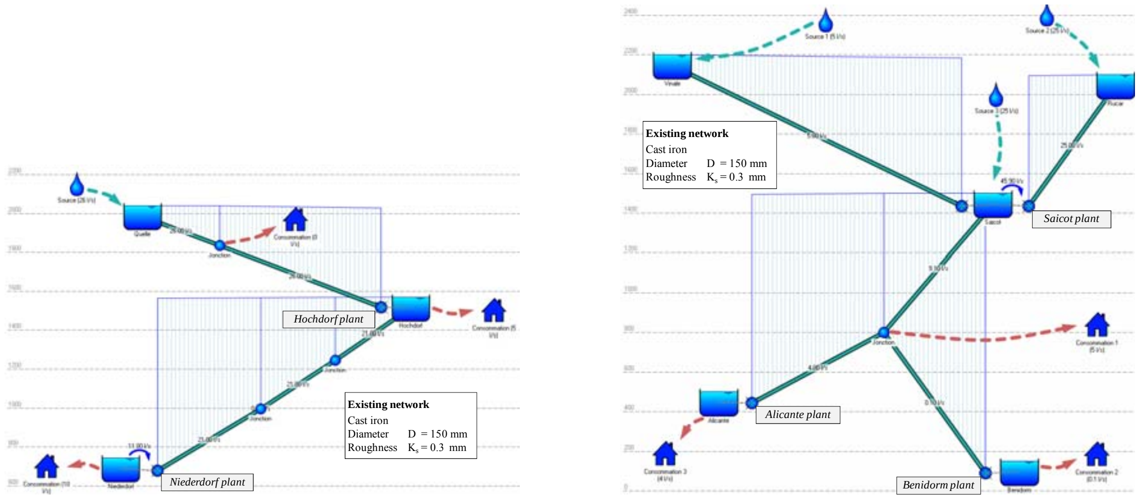

Fig. 4. Drinking water supply networks with hydropower schemes: Serial one (on the left) and parallel one (on the right).

3.1 Serial network

In the village of *Niederdorf* in the Swiss Alps, the drinking water is supplied by the partially glaciated catchment area of a small river. The inflow varies between 110 l/s in summer and 10 l/s in winter. The difference in altitude between the highest reservoir and the village is of about 1'400 m. The captured source at *Quelle* supplies the hamlets *Hochdorf* and *Hochalp*. The existing network consists of old cast iron pipes (roughness K_s=0.3 mm), which has to be replaced in the next few years. In this prospect, the economic turbining potential of the network had to be analysed. Two places are possible for the turbines, upstream the reservoirs of *Hochdorf* and *Niederdorf*. Two of the preliminary simulations done by TURBEAU are presented here.

The first task was an evaluation of economical feasibility without changing the pipes. The default values were used for the computation and several design flows were tested for both power plants. The results show that turbining 70 l/s is economically most attractive (Tab. 3). The important difference of the cost price between the optimistic and pessimistic scenarios shows the importance of the investments for access and linking to the electricity network.

Tab 3. Optimisation of design flow by TURBEAU for the two power plants of Niederdorf.

Design flow [l/s]	Hochdorf power plant				Niederdorf power plant			
	Cost price [cts/kWh]		Gains [CHF]		Cost price [cts/kWh]		Gains [CHF]	
	OPT	PES	OPT	PES	OPT	PES	OPT	PES
20	5.2	7.6	74'000	56'100	4.5	6.6	132'400	105'700
30	5.1	7.4	99'200	75'900	4.2	6.4	181'100	144'400
50	4.9	7.3	140'100	106'100	3.3	5.7	273'700	217'900
60	4.8	7.3	153'900	116'200	2.9	5.4	308'300	245'800
70	**4.7**	**7.2**	156'400	118'700	**2.9**	**5.3**	312'900	250'500
OPT = optimistic scenario, PES = pessimistic scenario								

In a second step, the network has been analysed when replacing the pipes. The costs were taken into account by the hydropower project. The final solution was then compared to real market prices. For the power plant of *Hochdorf* an increase of diameter to 300 mm (upper pipe) respectively 250 mm is foreseen. The optimal alternative of *Niederdorf* shows pipes with higher diameters as well, 200 mm, 250 mm and 300 mm. The roughness of the new PVC pipes is of 0.05 mm. Both turbines are designed for 70 l/s. Comparing to market prices, the TURBEAU costs reveal globally underestimated. The main difference is due to particularly difficult local conditions for installation of the pipes. Even when some amounts differ, the programme allows a useful global analysis.

Tab 4. Comparison of real costs and cost estimations of TURBEAU.

Element	Hochdorf power plant			Niederdorf power plant		
	Real Costs [CHF]	TURBEAU [CHF]	Difference [CHF]	Real Costs [CHF]	TURBEAU [CHF]	Difference [CHF]
Electromec. equipment	470'000	579'100	109'100	530'000	649'900	119'900
Construction site	600'000	36'600	-563'400	690'000	71'900	-618'100
Powerhouse/access	620'000	366'000	-254'000	405'000	719'400	314'400
Pipes (installation)	2'000'000	1'090'700	-909'300	2'220'000	763'900	-1'456'100
Electrical connection	135'000	90'000	-45'000	45'000	90'000	45'000
Study costs	450'000	857'800	407'800	395'000	1'196'200	801'200
TOTAL	4'275'000	3'020'300	-1'254'700	4285000	3'491'300	-793700

3.2 Parallel network

The task for the parallel network of another Alpine village is the evaluation of two power plants downstream *Sacont*, *Alicante* and *Benidorm*. The exceeding water had to be distributed between the plants in the most economic manner. In addition, the simulations with TURBEAU should decide, which pipes have to be replaced.

Tab 5. Comparison of different scenarios of water distribution between Alvicante et Benidorm (pessimistic scenarios).

Case	Existing pipe (K_s = 0.3 mm)				New pipe (K_s = 0.05 mm)			
	Diameter [mm]	Design flow [l/s]	Cost price [cts/kWh]	Gains [CHF/year]	Diameter [mm]	Design flow [l/s]	Cost price [cts/kWh]	Gains [CHF/year]
70% Alicante	150	80	3.3	478’000	**150**	**90**	**3.4**	**524’000**
30% Bendiorm	**150**	**40**	**5.1**	**265’000**	150	40	6.0	242’000
50% Alicante	150	70	3.6	441’000	**200**	**70**	**3.6**	**507’000**
50% Benidorm	**150**	**50**	**4.5**	**378’000**	200	50	5.0	377’000
30% Alicante	150	60	4.0	376’000	**200**	**60**	**4.4**	**396’000**
70% Benidorm	**150**	**60**	**3.1**	**517’000**	200	50	3.7	497’000
100% Alicante	150	110	4.2	494’000	**150**	**110**	**3.1**	**585’000**
100% Benidorm	**150**	**60**	**2.9**	**571’000**	200	50	3.3	571’000

Three iterations with 30%/70%, 50%/50% and 70%/30% scenarios have been done. The optimal use of power resources is obtained by turbining 70% of the flow at *Benidorm*. The distribution pipe to *Alicante* has to be replaced for reducing friction losses (new diameter 200 mm). For the one to *Benidorm*, there is no need for such a measure. Both turbines show an optimal economic output for design flows of 60 l/s. The annual gain is about CHF/year 900'000. If only one of the plants could be realized, the *Alicante* hydro power scheme is the most attractive.

4. Conclusion

TURBEAU is a numerical tool helping water network owners to evaluate the hydropower potential of their systems with a minimum of input data. The reference to a wide database fits the lack of specific data. The overall analysis does however not replace the detailed study of a potential economically interesting plant. The main advantage of TURBEAU is its user friendliness, especially the graphic interface for an easy understanding of complex networks. The quick modelling allows the analysis of several alternatives in a short time. The results are generated interactively and provide focusing on the appropriate points. Additional information about the TURBEAU software is available at the authors.

References

1. **Chapallaz, J.-M., et al.,** “Petites centrales hydrauliques”, *Office fédéral des questions conjoncturelles*. ISBN3-905232-20-0, 1995, Switzerland.
2. **Keady, G.,** “The Colebrook-White formula for pipe networks”, *Engineering Transaction. Inst. Eng.* 1995, Australia.
3. **Office fédéral de l’énergie (OFEN),** “Loi sur l’approvisionnement en électricité (LApEl) 734.7”, *Feuille Fédérale* of 3rd of April 2007, Switzerland.

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